

# **An Investigation of Non-Bragg Scattering from the Sea Surface**

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## **LONG-TERM GOALS**

The long-range objective of this work is to investigate non-Bragg sea surface scattering at intermediate angles of incidence. We seek to define the characteristics of these scatterers and to establish a link between radar observations and the underlying physical processes.

## **OBJECTIVES**

Our objective is to investigate scattering from the sea surface that seemingly cannot be explained using composite surface models based on Bragg scattering theory. The majority of models for predicting radar backscattering from the sea surface are based on Bragg scattering. These models adequately predict most backscatter observations, but several phenomena are not well predicted using this type of approach, suggesting the models exclude some relevant physical processes. This research seeks to develop a metric to identify scattering events that are inconsistent with composite surface theory, and to determine whether the characteristics of these scatterers vary as a function of environmental conditions or radar parameters. We aim to identify prospective mechanisms and to develop predictive models for these non-Bragg scatterers.

## **APPROACH**

Our approach is to analyze data from the SAXON-FPN experiment conducted in 1990/1991 (described in detail by Plant and Alpers, 1994) to define the characteristics of non-Bragg sea surface scattering. This data set includes simultaneously acquired horizontally (HH) and vertically (VV) polarized radar cross-section observations at Ka, Ku and X-band, as well as detailed environmental measurements. One common means of separating Bragg and non-Bragg scattering has been to observe the ratio of HH to VV cross sections. Since Bragg scattering predicts that on average VV cross sections should be larger than HH ones at moderate incidence angles, a common practice has developed in which any scattering for which the HH cross section is larger than the VV one is designated as non-Bragg scattering. We examine whether the ratio of HH-to-VV is a valid criterion for designating non-Bragg

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scattering events through statistical analysis of the observations and by comparing the data with simulations based on composite surface theory.

## WORK COMPLETED

Last year, we obtained an extensive archive of SAXON-FPN Phase I and Phase II data that had been stored at the original sample rate of 3 kHz. For the Phase I data, the radar was looking nearly into the wind (within  $45^\circ$  of the wind direction). For Phase II, the selected data included cases where the radar was looking into the wind and also orthogonal to the wind. For Phase I, the incidence angle was fixed at  $45^\circ$ ; during Phase II, the angle of incidence was varied. We started with data that had not been down-sampled or averaged, in order to evaluate the impact of averaging on the frequency of events for which  $HH > VV$ , both in Ka- and X-band data. We observed that the frequency of occurrence of  $HH > VV$  depended strongly on the extent of decimation or averaging time, consistent with the observations of other researchers (e.g., Jessup et al. (1991), Rufatt (1999)). This dependence led us to look more closely at whether the criterion  $HH > VV$  was an appropriate basis for designating non-Bragg scattering, particularly at shorter time scales.

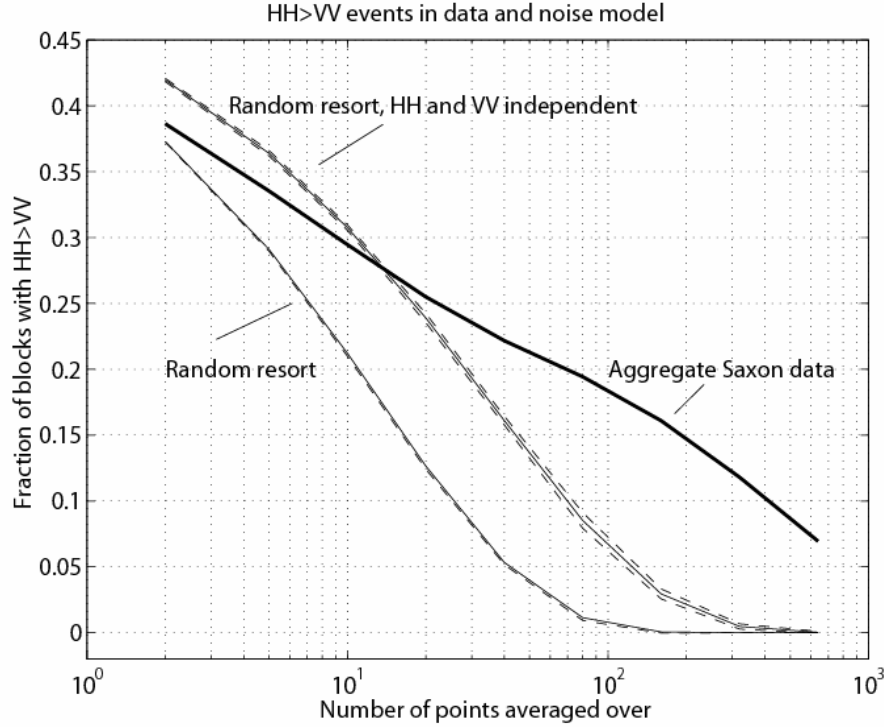
Furthermore, given the effects of tilting, modulation and signal fading, the condition  $HH > VV$  is not inconsistent with Bragg scattering theory, if sufficiently short averaging times are considered. These observations prompted us to seek a more appropriate criterion for identifying non-Bragg scattering events than  $HH/VV > 1$ . Pursuant to defining such a criterion, we performed the following series of investigations: For the Ka-band, Phase I SAXON-FPN data, we examined the conditional probability distribution function of  $HH$  given a particular partition of  $VV$ , at a variety of sample rates. These same backscatter observations were compared with model predictions obtained using a Bragg-based simulation. The probability densities of  $HH/VV$  for these observations and model predictions were also compared. In addition, we obtained a series of Monte Carlo simulations to determine the effects of averaging length on the probability of  $HH > VV$ , given the inherent random variability of the data. These investigations are still ongoing.

## RESULTS

In order to focus on the gross characteristics of the data, i.e., behavior not linked to particular environmental conditions, and to obtain large data sets, we produced a suite of secondary data sets by aggregating all individual runs for a particular day of the experiment. In Figure 1 we consider one such data set, which is an aggregate of all the runs obtained on 18 November 1990. On this day, the wind speed varied between approximately 12 and 18  $\text{ms}^{-1}$ . This plot examines how  $HH > VV$  varies as a function of averaging length. Here, the original data have been decimated to 200 Hz. For each averaging length  $L$ , the data of length  $N$  has been broken up into approximately  $N/L$  blocks, and the fraction of blocks for which  $\langle HH \rangle$  is greater than  $\langle VV \rangle$  is then plotted, where  $\langle \rangle$  denotes averaging. Comparing these results with similarly averaged random resorts of the original data sequence enables us to assess, for a given averaging length, the relative fraction of  $HH > VV$  events which cannot be explained solely on the basis of the inherent variability of the data.

Two different Monte Carlo simulations, that characterize the sequence variability, were obtained by resorting the original sequence in a random order, as shown in Figure 1. For the lower curve, the data sequence has been resorted in random order, but the pairings of individual  $HH$  and  $VV$  observations have been preserved. The upper curve obtains an analogous resorting, but in this case the  $HH$  and  $VV$

sequences have been resorted independently. Because the original sequence consisted of a sufficiently large sample ( $>800,000$  observations), only 10 resorting realizations were necessary.



**Figure 1.** The solid line depicts the fraction of events in an aggregated SAXON-FPN data file (11/18/90) for which  $HH > VV$ , as a function of averaging length. The curves labeled as ‘random resort’ are Monte Carlo simulations representing upper bounds to estimates of the noise. The dashed lines represent  $\pm$  one standard deviation.

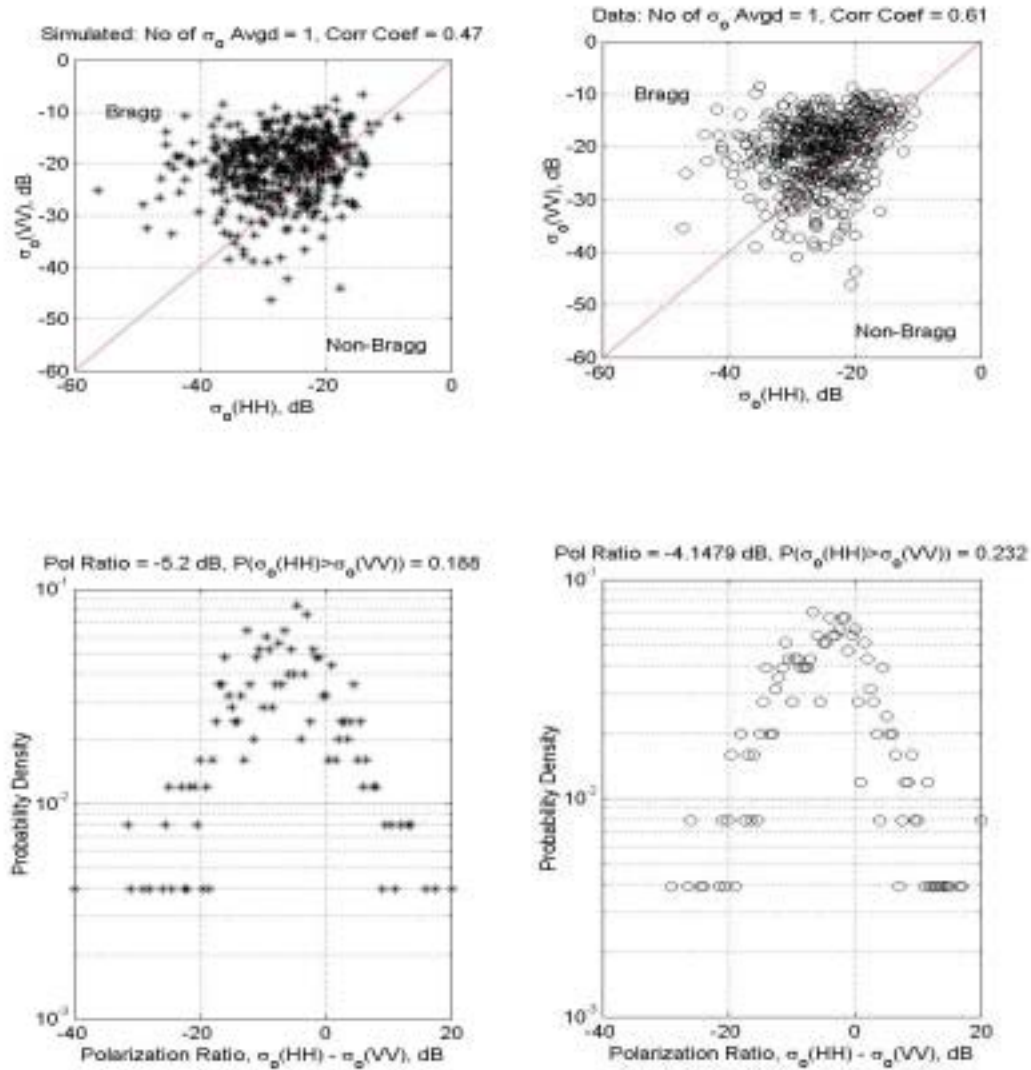
The difference between the ‘Aggregate SAXON’ data curve and the upper resorted curve is an estimate of the number of  $HH > VV$  events that arose in the data, that cannot be accounted for, based exclusively on the random variability of the data. Comparing these two curves, we see that for averaging lengths greater than 50 samples (0.25 s) m,  $HH > VV$  more than 20% of the time, and nearly half of these events cannot be accounted for by random variation in the measurements. In order to determine whether or not these observations are attributable to non-Bragg scattering, it is necessary to compare these observations with Bragg-based model predictions, and to make use of models that address signal variability, such as Rayleigh fading, and noise.

It is worth noting that the noise curve in which individual  $HH$ - $VV$  pairings were preserved exhibits behavior consistent with what one would expect from a scene dominated by Bragg-type scattering, namely, an individual  $VV$  observation will tend to exceed its  $HH$  counterpart, or the fraction of blocks with  $HH > VV$  is substantially lower than the fully randomized case.

In order to make a valid comparison between  $HH$  and  $VV$  cross sections, it is essential to understand the role of phase in the received fields. Because any ocean surface area illuminated by a microwave signal will necessarily contain a large number of decorrelated scatterers, the total received field will exhibit Rayleigh fading due to the vector addition of fields from individual scatterers. To compare  $HH$

and VV cross sections, for phase-locked transmitted signals at the two polarizations, the phases from every scatterer that contributes to the total received field must match exactly. This means that the illuminated areas, incidence angles, and times of data collection at the two polarizations must match exactly, a difficult situation to achieve. The systems used during SAXON-FPN experiment had a 60 MHz offset between the transmitted HH and VV signals. This was incorporated so that the simultaneously received signals could be separated based on frequency. Thus the phases of the HH and VV transmitted signals in our setup are perfectly decorrelated rather than being phase locked. This has proven to be a big advantage in modeling the returns since phases of individual scatterers in the HH return signal can safely be assumed to be decorrelated from those in the VV return.

Using this advantageous feature of the data, we have simulated the backscatter from the ocean by assuming that the amplitude of the field scattered from each scatterer within the illuminated spot is the square root of the Bragg scattering cross section and that the phases are perfectly decorrelated.



**Figure 2.** The left column shows simulated backscatter assuming Bragg scattering; the right column shows data obtained during SAXON-FPN. The top row shows VV cross sections plotted against HH while the bottom row shows the probability distribution of the polarization ratio. The incidence angle is  $45^\circ$ ; the antenna is directed into the wind, and the wind speed is 6.5 m/s.

We have compared the results of our simulation with data collected during SAXON-FPN and show the comparison in Figure 2 for the case where the averaging time is smaller than the decorrelation time (<about 10 msec). Clearly data and simulation display very similar characteristics at this 45° incidence angle looking into the wind. We have obtained similar results at higher incidence angles and other azimuth angles, however.

In the top plots, one can see that the scatter of data in the Bragg scattering simulation is very similar to that of the actual data. The division into “Bragg” and “Non-Bragg” based on the location of a data point with respect to the red diagonal line is meaningless in this simulation; it is equally meaningless in the actual data. The lower plots illustrating the distribution of values of the HH/VV polarization ratios also illustrates that pure Bragg scattering predicts that this ratio is frequently greater than zero. The probability of having HH greater than VV is similar in the data and simulation. As the averaging time is increased, the scatter of the points on the top plots decreases and the distributions in the lower plots narrow. Only for a very long averaging time does Bragg scattering really predict that HH cross sections will never be larger than VV.

The conclusion to be drawn from this work is that detecting HH cross sections that are larger than VV cross sections is not proof of non-Bragg scattering. Only if the probability of such events in the data is significantly higher than indicated by a Bragg scattering simulation can we possibly infer from polarization data that scattering processes other than Bragg have been observed; if the Bragg scatterers are tilted, even this may not suffice.

## **IMPACT/APPLICATION**

This project will lead to an improved understanding of the physical processes responsible for observed radar returns from the sea surface as a function of radar viewing parameters and viewing conditions.

## **TRANSITIONS**

The results of this project have not yet been transitioned for operational use.

## **RELATED PROJECTS**

This project is directly related to NASA scatterometers, such as QuikScat, and are relevant to the study of sea surface scattering, particularly at high wind speeds.

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